Summer 8-2018

Band-Sowing with Hoeing for Weed Management in Organic Grains

Margaret R. McCollough
University of Maine, margaret.mccollough@maine.edu

BAND-SOWING WITH HOEING FOR WEED MANAGEMENT IN ORGANIC GRAINS

By

Margaret R. McCollough

B.S. University of Maine, 2015

A THESIS

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

(in Ecology and Environmental Sciences)

The Graduate School

The University of Maine

August 2018

Advisory Committee:

Eric Gallandt, Professor of Weed Ecology and Management, Advisor

Ellen Mallory, Associate Professor of Sustainable Agriculture and Cooperative Extension

Sustainable Agriculture Specialist

Gregory Porter, Professor of Crop Ecology and Management

BAND-SOWING WITH HOEING FOR WEED MANAGEMENT IN ORGANIC GRAINS

By Margaret R. McCollough

Thesis Advisor: Dr. Eric R. Gallandt

An Abstract of the Thesis Presented
in Partial Fulfillment of the Requirements for the
Degree of Master of Science
(in Ecology and Environmental Sciences)

August 2018

Weeds remain the foremost production challenge for organic small grain growers in the Northeastern United States. Instead of sowing crops in narrow, single-line rows, band-sowing with inter-band hoeing is a cropping strategy that could provide superior weed control. In theory, band-sowing suppresses weeds in the intra-band zone by improving the spatial arrangement of the crop from that of typical rows to a more uniform pattern within the planted bands, maximizing interspecific and reducing intraspecific competition. Weeds in the inter-band zone are controlled by cultivating with aggressive sweeps; tine harrowing can target weeds in the intra- and inter-band zones.

Chapter one addresses field experiments performed in Maine and Vermont in 2016 and 2017 to evaluate band-sowing for its ability to control weeds and enhance yields in spring barley (*Hordeum vulgare* L. 'Newdale'). Five treatments were compared: the region's standard practice for growing organic cereals, narrow-row high density planting, wide-row planting with inter-row hoeing, band-sowing without inter-band hoeing, and band-sowing with inter-band hoeing. Mustard (*Sinapsis alba* L. 'Ida Gold') was sown uniformly throughout the experiment as a surrogate weed. Band-sowing with inter-band hoeing reduced surrogate weed density on average by 48% compared to the standard practice, however, the effect on weed biomass was inconsistent. Suboptimal timing of hoeing, and adverse weather conditions may have contributed to the lack of consistent treatment effects.

Optimization of band-sowing is likely possible, and it is recommended that band-sowing be further investigated prior to advocating its use to organic cereal growers.

Chapter two addresses field experiments performed in Maine in 2016 and 2017 that compared two treatments: band-sowing with inter-row hoeing, and the region's standard practice. Treatment effects on weeds and yield were evaluated in multiple grain crops: spring wheat (*Triticum aestivum* L. 'Glenn'), oat (*Avena sativa* L. 'Colt'), field pea (*Pisum sativum* L. 'Jetset'), and flax (*Linum usitatissimum* L. 'Prairie Thunder'). Band-sowing improved weed control relative to the standard practice; crops with greater competitive ability (wheat and oat) performed superior to less competitive crops (field pea and flax). In most cases, yields were unaffected by treatment, exceptions being: band-sowing increased oat yield by 6%, and decreased field pea yield by 35% in separate years.

ACKNOWLEDGEMENTS

The author expresses her sincere gratitude to her advisor, Dr. Eric Gallandt, for his mentorship and support throughout both her undergraduate and graduate career. The author would also like to thank her committee members, Drs. Ellen Mallory and Gregory Porter for their thoughtful feedback and guidance. Gratitude is extended to Tom Molloy and Joe Cannon for their tremendous help implementing experiments. To fellow graduate students, Sonja Birthisel, Margaret Pickoff, and Bryan Brown, the author thanks you for the many contributions you've made as colleagues. To collaborators at the University of Vermont, whose replication of experiments described in this thesis were integral, Heather Darby, Erica Cummings, and Roger Rainville, thank you. The author also extends her thanks to those who have contributed as research assistants and volunteers, who have helped with data collection in the field and in the lab, Geena Wright, Sam Sheppard, Annika Gallandt, Isaac Mazzeo, Katie O'Brian, Jake Cormier, Grace Smith, Lucia Helder, Garth Douston, Becca Gallandt, Liza Gallandt, Cathy Elliott, Leala Manchesney, Amelia Remillard, and Catherine Doheny, thank you. This work was supported by the USDA National Institute of Food and Agriculture, Organic Agriculture Research and Extension Initiative Competitive grant, "Innovative sowing, cultivation, and rotation strategies to address weed, fertility and disease challenges in organic food and feed grains." Accession Number 1007233; E. Mallory, Project Director.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ABBREVIATIONS

ai	active ingredient
ANOVA	analysis of variance
ANCOVA	analysis of covariance
bu	bushel
C	Celsius
cm	centimeter
g	gram
ha	hectare
kg	kilogram
L	liter
lb.	pound
LSD	least significant difference
m	meter
mm	millimeter
no.	number
POST	post-emergence
ppm	parts per million
PRE	pre-emergence
SE	standard error

CHAPTER 1

COMPARISON OF BAND-SOWING WITH HOEING AND ALTERNATIVE WEED MANAGEMENT PRACTICES IN ORGANIC SPRING BARLEY

Introduction

Demand for locally produced organic cereals is on the rise in the Northeastern United States. Growing markets for organic livestock feed, local artisan foods, and craft malt products has resulted in an increase in the price of small grains, and in response, farmers are increasing production. Weeds, however, remain a challenging production problem in organic grains.

Cereals are typically planted in rows spaced 15 to 18 cm apart, and PRE and POST tine harrowing is performed when weather conditions permit. Despite its popularity, the efficacy of tine harrowing is quite variable (Gallandt et al. 2018). Given ideal conditions, tine harrowing can achieve satisfactory weed control of 80 to 90% (Rasmussen 2004; Lundkvist 2009). Efficacy is reduced, however, as soil moisture increases (Kurstjens and Kropff 2001), and as weeds grow larger, surpassing the white thread stage and becoming better established (Baerveldt and Ascard 1999; Kurstjens et al. 2000; Lundkvist 2009). Tine harrowing is also less effective on taprooted weed species with an erect growth habit (Melander et al. 2003), such as wild radish (*Raphanus raphanistrum* L.) (Warwick and Francis 2005), a particularly problematic weed in small grains (see Cheam et al. 2008). Tine harrows are often referred to as “blind” cultivators because they administer uniform disturbance to the entire field. POST harrowing ideally results in the uprooting and burial of smaller weeds, with less damage to the larger, better established crop. A trade-off consequently exists when POST tine harrowing between potential yield benefits resulting from reduced weed density and yield losses resulting from burial or uprooting of the crop (Rasmussen 1991; Melander et al. 2005; Lundkvist 2009; Rasmussen et al. 2009; Kolb and Gallandt 2012).

Kolb et al. (2010, 2012) previously identified two improved cropping strategies for managing weeds in organic cereals: narrow-row planting at a high density seeding rate (11 cm rows, receiving PRE and POST tine harrowing) and wide-row planting with inter-row hoeing (23 cm rows, receiving PRE and POST tine harrowing and inter-row hoeing). The narrow-row, high density system improved weed control by enhancing competition through elevated seeding rates and altered crop spatial arrangement, and the wide-row system with inter-row hoeing improved weed control by utilizing hoes, a more robust and aggressive physical weed control tool compared to tine harrows (Kolb et al. 2010, 2012). The wide-row system reduced weed biomass by 22 to 54%, and the narrow-row, high density system reduced weed biomass by 45 to 60% when compared with the region's standard cropping strategy (18 cm rows, receiving PRE and POST tine harrowing) (Kolb et al. 2010, 2012).

Band-sowing offers an alternative to wide-row planting with hoeing (see, System Cameleon, Gothia Redskap AB, Fornåsa, Sweden). Band-sowing aims to improve weed control by leveraging the tactics that separately improve weed control in the previously described narrow-row and wide-row systems. The crop is broadcast in bands 5 to 20 cm wide instead being sown in a row (Speelman 1975; Andersson 1986; Huhtapalo 1986; Heege 1993). Altering the crop's spatial distribution from a "rectangular" arrangement to a more "uniform" broadcast arrangement decreases adverse intraspecific competition amongst crop plants, and increases interspecific competition occurring between individual crop plants and weeds, thus elevating weed suppression (Fischer and Miles 1973; Speelman 1975; Regnier and Bakelana 1995; Weiner et al. 2001).

In a band-sowing system, the inter-band zone can be cultivated with sweeps. When compared with tine harrows, sweeps are a more effective physical weed control tool in varying soil conditions, and across a wider range of weed species and life stages (Pullen and Cowell 1997; Melander et al. 2003). When the crop is planted in bands, cultivation sweeps may be operated closer to the established crop than possible with row-sown arrangements. When hoeing between crop rows, 3 to 6 cm is often left uncultivated on either side of the row to reduce the risk of crop mortality due to cultivator misguidance (Melander et al. 2001, 2003; Kolb et al. 2010, 2012). In theory, it is possible to operate sweeps right up to the band's edge, perhaps sacrificing occasional crop plants, but cultivating a greater proportion of the inter-band zone than is possible with inter-row hoeing (L Askling, Gothia Redskap AB, personal communication).

Band-sowing also addresses a disadvantage of wide-row planting, specifically reduced yields resulting from the elevated interspecific competition associated with increasing the rectangularity of the crop's spatial arrangement (Melander et al. 2003, 2001). Welsh et al. (2002) proposed that band-sowing may mitigate yield losses associated with wide-row planting by reducing intraspecific competition; in agreement, cereal yields up to 4.9% greater than achieved with row-planting have been observed with band-sowing (Speelman 1975; Andersson 1986; Huhtapalo 1986; Heege 1993). Field studies performed by Anderson (1986) in Sweden found that altering the spatial arrangement of spring barley from rows to bands provided improved weed control, however, no differences were detected between the two planting arrangements in spring and winter wheat crops.

Despite strong theoretical rationale in support of combining band-sowing and inter-band hoeing to achieve enhanced weed control, the efficacy of this strategy has not been explicitly tested. In this study we compared five strategies to manage weeds in organic barley: (i) the region's standard practice (16.5 cm rows), (ii) narrow-row, high density planting (11.4 cm rows), (iii) wide-row planting with inter-row hoeing (22.8 cm rows), and band-sowing with (iv) and without (v) inter-band hoeing (12.7 cm crop bands, 15.2 cm between planted bands). All treatments were planted at a target population 325 plants m^{-2} with the exception of the narrow-row high density treatment, sown at 500 plants m^{-2}, and all treatments received POST tine harrowing. Our objectives were to assess the effect of each cropping strategy on weed density and biomass, crop yield, and grain quality parameters. We hypothesized that: (i) the wide-row and narrow-row strategies would provide superior weed control and increased yields when compared with the region's standard cropping practice as previously reported (Kolb et al. 2010, 2012); and (ii) band-sowing with inter-band hoeing would further improve weed control and yields.

Materials and Methods

Site Characteristics and Field Preparation

Field experiments were performed in Old Town, Maine (44.93°N, 68.70°W), and Alburgh, Vermont (45.01°N, 73.31°W) in 2016 and 2017. At the Maine site in 2016, the experiment was conducted in a field consisting of a Nicholville very fine sandy loam; in 2017, the field was a Pushaw-Boothbay complex soil type. In the year preceding the experiment at the Maine site, fields were planted to oat (*Avena sativa* L.) in 2015 and potato (*Solanum tuberosum* L.) in 2016. At the Vermont site, the soil was a Covington silty clay loam; fields were planted to corn (*Zea mays* L.) in 2015 and winter canola (*Brassica napus* L.) in 2016. All fields were managed organically in the year prior to establishing experiments, except for the potatoes grown at the Maine site in 2016 that received applications of metribuzin (Sencor 75 DF®, 1.7 g ai L^{-1}, Bayer CropScience Inc., Whippany, New Jersey, United States) and s-metolanchlor (Charger Max®, 3.8 g ai L^{-1}, WinField United, Arden Hills, Minnesota, United States).

Soil fertility was amended based on soil test results. In Maine, solid dairy manure was applied at 73 kg ha^{-1} of plant-available nitrogen. In Vermont, commercial fertilizers were used to amend soil fertility. In 2016 Cheep Cheep 4-3-3 (North Country Organics, Bradford, Vermont, United States) was applied at 90 kg ha^{-1} of plant-available nitrogen, and in 2017 Pro-Grow 5-3-4 (North Country Organics, Bradford, Vermont, United States) was applied at 112 kg ha^{-1} of plant-available nitrogen. Seedbeds were prepared with a Perfecta® Field Cultivator (Unverferth Manufacturing Company Inc., Kalida, Ohio, United States) at the Maine site, and with a spike tooth harrow at the Vermont site, with final operations occurring within 12 hours of planting.

Experimental Design and Treatment Specifications

Treatments were established in a randomized complete block design, with five replications in Maine, and four in Vermont. Two-row spring malting barley (*Hordeum vulgare* L. 'Newdale') was used as the test crop. Five treatments were included in the experiment, all of which received POST tine harrowing when possible. At the Maine site, harrowing was performed using a Williams Tool System spring tine harrow (Market Farm Implement, Friedens, Pennsylvania, United States); at the Vermont site, a Kovar Cone Coil spring tine harrow (Kovar Organic Equipment, Franklin, Pennsylvania, United States) was used. Both harrows had 6 mm tines.

The five treatments will be referred to as Standard, Narrow HD, Wide +, Band, and Band +. The Standard treatment aimed to represent the standard practice for growing cereal crops in northern New England; row spacing was 16.5 cm, with a target crop density of 325 plants m^{-2}. At the Maine site, the Standard treatment was sown using a grain drill with double-disc openers (H & N Equipment, Colwich, Kansas, United States). At the Vermont site, the Standard treatment was planted using a Sunflower 9412 grain drill (Sunflower Manufacturing, Beloit, Kansas, United States), also with double-disc openers. Narrow HD consisted of a narrow-row, high density planting in which row spacing was decreased to 11.4 cm and the target crop density increased to 500 plants m^{-2}. Wide + was a wide-row planting with inter-row cultivation where row spacing was increased to 22.8 cm to accommodate inter-row hoeing, and the target crop density was 325 plants m^{-2}. Hoeing at both locations was performed using a Schmotzer cultivator (Maschinenfabrik Schmotzer GmbH, Windsheim, Germany), with a manual guidance system and 12.7 cm sweeps. At the Maine site, both the Narrow HD and Wide + treatments were planted using a Vicon air seeder (Kverneland Group, Klepp Stasjon, Norway) with shoe openers; at the Vermont site, a Kverneland Accord DL grain drill (Kverneland Group, Klepp Stasjon, Norway) with single-disc openers was used. To plant in narrow rows, for the Narrow HD treatment, all planting shoe openers were used. To produce wide rows, as in the Wide + treatment, every other opener was disabled.

Band-sown treatments were sown to a target crop density of 325 plants m^{-2}. At the Maine site, band-sown treatments were planted using the Vicon air seeder modified with Dutch Openers (Dutch Industries Ltd., Pilot Butte, Saskatchewan, Canada), broad-shoe openers capable of sowing the crop in 12.7 cm bands; 15.2 cm was left between the planted bands, therefore, band spacing center-to-center was 27.9 cm. At the Vermont site, band-sown treatments were planted using a custom built air seeder constructed from a Case IH 8-row, row crop cultivator toolbar and parallel linkage units (CNH Industrial America LLC, Burr Ridge, Illinois, United States) and a Gandy 6212 Orbit-Air seeder (Gandy Company, Owatonna, Minnesota, United States), also with Dutch Openers. The Band treatment did not receive inter-band cultivation whereas the Band + treatment was cultivated using the Schmotzer cultivator with 12.7 cm sweeps.

After the barley was planted, condiment mustard (*Sinapsis alba* L. 'Ida Gold') was sown in all plots as a surrogate weed at a target density of 65 plants m^{-2} (Kolb et al. 2010). At the Maine site, condiment mustard was planted using a Brillion Sure Stand Grass Seeder (Landoll Corporation, Marysville, Kansas, United States); at the Vermont site mustard was broadcast by hand.

Data Collection

Three 0.25 m^{-2} permanent quadrat locations were randomly placed within the central area of each plot; these sites were returned to throughout the experiment to measure crop, ambient weed, and surrogate weed density, and biomass.

Crop and Surrogate Weed Populations. Initial censuses of the crop and surrogate weeds were performed prior to POST tine harrowing. Crop censuses were conducted along three permanently marked 0.5 m lengths of row or band in each plot, and weed censuses were performed within the three permanent quadrat locations.

Surrogate Weed Density and Biomass, and Ambient Weed Biomass. Prior to harvest, all above-ground plant biomass within permanent quadrats was cut 13 mm from the soil surface and collected. Crop, surrogate weeds, and ambient weeds were separated, and final censuses was performed for the crop and surrogate weeds. Plant material was dried at 49°C for at least 7 days and weighed.

Barley Yield. At the Maine site, barley was harvested with a Wintersteiger Classic plot combine (Wintersteiger Inc., Salt Lake City, Utah, United States) and at the Vermont site an Almaco SPC 50 small plot combine (Almaco, Nevada, Iowa, United States). Grain samples were cleaned using a Clipper Model 400 Office Tester and Cleaner (Seedburo Equipment Co., Des Plaines, Illinois, United States) at the Maine site, and a Clipper M2B cleaner (A.T. Ferrell, Bluffton, Indiana, United States) at the Vermont site. Grain moisture was measured in Vermont using a DICKEY-john M20P moisture tester (DICKEY-john, Auburn, Illinois, United States) and a DICKEY-john GAC 2100 Agri (DICKEY-john, Auburn, Illinois, United States) in Maine. Yield data was standardized and presented at 13.5% moisture content.

Barley Quality. Barley test weight was obtained using the DICKEY-john GAC 2100 Agri at the Maine site, and a Berckes Grain Test Weight Scale (Berckes Mfg., Canby, Minnesota, United States) at the Vermont site. Thousand kernel weight was acquired by counting 1,000 barley kernels and recording their mass. The US Department of Agriculture, Grain Inspection, Packers and Stockyards Administration grain grading procedure 2.23 (USDA, GIPSA 2006) was used to measure the proportion of plump barley kernels. Germination energy was assessed according to the American Society of Brewing Chemists, Barley-3 methods (ASBC 1958). A ground sub-sample of barley was used to determine grain protein and Deoxynivalenol mycotoxin (DON) levels. In Vermont, crude protein was measured using a Perten Infamatic 8600 Flour Analyzer (Perten Instruments, Springfield, Illinois, United States). In Maine, N concentration was measured using the combustion method (Sweeney 1989), and crude protein was calculated by multiplying % N by 6.25 (ASBC 2011). DON levels were evaluated at the Vermont site using a Veratox® for DON 5/5 Quantitative Test (NEOGEN Food Safety, Lansing, Michigan, United States), and using a Charm ROSA DONQ2 Quantitative Test (Charm Sciences Inc., Lawrence, Massachusetts, United States) at the Maine site. No evidence of infection by DON-mycotoxin-producing Fusarium head blight

(*Fusarium* species) was observed in either experimental year at the Maine site, therefore, an aggregate sample containing equivalent sub-samples from all treatment plots was tested. In both the Maine 2016 and 2017 site-years the aggregate sample contained less than 0.1 ppm, thus no additional testing was conducted.

Analysis

Data were analyzed using JMP® 10.0.2 software (SAS Institute Inc., Cary, North Carolina, United States). Each site-year (Maine 2016, Vermont 2016, Maine 2017, and Vermont 2017) was analyzed separately due to significant treatment by site-year interactions as well as differences in the number (Table 1.1) and timing (Table 1.2) of cultivation events. An alpha level of 0.05 was used throughout for hypothesis testing.

Surrogate weed density, surrogate weed biomass, ambient weed biomass, and barley yield data were analyzed using ANOVA with subsequent pre-planned contrasts for hypothesis testing. Variables used in ANOVA analyses included block and treatment. To ensure data met the assumptions of ANOVA, including normal distribution and equality of variance of residuals, Shapiro-Wilk's and Levene's tests were performed, respectively. When necessary, square-root, square-root (x+3), $\log_{10}$, and $\log_{10}(x+1)$ transformations were performed to meet assumptions.

Grain quality parameters were analyzed with ANOVA, and Fisher's protected LSD was used to perform means comparisons. Variables used in ANOVA analyses included block and treatment. When needed, Arcsine transformations were performed to meet assumptions. If unable to meet the assumptions of ANOVA with transformations, data were analyzed using the non-parametric Kruskal-Wallis test, and the Wilcoxon signed-rank test was used to perform means comparisons.

Table 1.1. Cultivation events performed at Maine and Vermont sites in 2016 and 2017.

Year	Site	Treatment	Cultivation events		
			POST tine harrowing	First inter-row or band cultivation	Second inter-row or band cultivation
			no.		
2016	Maine	Standard	2	-	-
		Narrow HD	2	-	-
		Wide +	2	1	0
		Band	2	-	-
		Band +	2	1	0
	Vermont	Standard	1	-	-
		Narrow HD	1	-	-
		Wide +	1	1	0
		Band	1	-	-
		Band +	1	1	0
2017	Maine	Standard	2	-	-
		Narrow HD	2	-	-
		Wide +	1[a]	1[a]	1
		Band	2	-	-
		Band +	1[a]	1[a]	1
	Vermont	Standard	1	-	-
		Narrow HD	1	-	-
		Wide +	0	1	0
		Band	1	-	-
		Band +	0	1	0

[a]In the Maine 2017 site-year, the 1st inter-row or band cultivation event and POST harrowing were performed in sequence.

Table 1.2. Summary of dates and barley growth stages that field operations were performed.

Field operation	2016				2017			
	Maine		Vermont		Maine		Vermont	
	Date	Stage[a]	Date	Stage[a]	Date	Stage[a]	Date	Stage[a]
Fertilize	April 28		April 26		May 18		April 25	
Sow barley and surrogate weed	April 29		April 28		May 18		April 27	
POST tine harrowing	May 21	13	May 10	10-21	June 8	12	May 24	14-16
First inter-row or band cultivation	May 31	14, 22	May 24	30	June 8	12	May 24	14-16
Second inter-row or band cultivation	-		-		June 22	14-15, 21	-	
Peak biomass	July 19	85	July 27	85	July 26	87	August 1	87
Grain harvest	August 3		August 3		August 9		August 1	

[a]Barley growth stages are described using Zadock et al. (1974) decimal code for cereals.

Results and Discussion

Weather

Both Maine and Vermont sites had below average rainfall during the 2016 growing season, with the exception of July at the Maine site, when rainfall was 57% greater than the 30-year average (Table 1.3). In 2017, April and May were wetter than average at both sites, in addition, precipitation was 68% greater than normal in June at the Vermont site. Total rainfall during the months of June, July, and August was 49% less than average at the Maine site, and during the months of July and August at the Vermont site was 26% less than average.

Table 1.3. Total rainfall during the months of April – August at Maine and Vermont sites in 2016 and 2017 compared with 30-year means from 1988 to 2017.

Month	Total rainfall					
	2016		2017		30-year mean	
	Maine	Vermont	Maine	Vermont	Maine	Vermont
	mm					
April	63	32	104	98	87	65
May	77	42	124	114	91	85
June	65	94	68	176	100	105
July	119	91	47	80	76	99
August	62	78	43	65	74	97
Total	386	337	386	532	428	450

Crop and Surrogate Weed Populations

Increasing crop density has a negative effect on weed biomass (Doll 1997; Olsen et al. 2005a, 2005b). Due to differences between achieved and target crop densities (plants m^{-2}), the error (%) between achieved and target crop density for each plot (Table 1.4) was used as a continuous variable in ANCOVA analyses. The effect of error (%) between achieved and target crop density was non-significant ($p = >0.05$), however, and therefore this continuous variable was discarded from analyses.

Table 1.4. Crop population at Maine and Vermont sites in 2016 and 2017.

Treatment	2016				2017			
	Maine		Vermont		Maine		Vermont	
	Achieved density	Error[a]	Achieved density	Error[a]	Achieved density	Error[a]	Achieved density	Error[a]
	no. m^{-2}	%	no. m^{-2}	%	no. m^{-2}	%	no. m^{-2}	%
Standard	341	5	239	-26	435	34	197	-39
Narrow HD	709	42	569	14	589	18	467	-7
Wide +	288	-11	314	-3	331	2	257	-21
Band	375	15	289	-11	296	-9	362	11
Band +	370	14	269	-17	282	-13	404	24

[a]Error = (achieved density – target density) / target density. Target density for barley in the Standard, Wide +, Band, and Band + treatments was 325 no. m^{-2}, and for the Narrow HD treatment was 500 no. m^{-2}.

Surrogate Weed Density

In support of our hypothesis that band-sowing and hoeing would improve weed control relative to the region's standard practice, the Band + treatment reduced surrogate weed density (no. m^{-2}) compared to the Standard treatment in all measured site-years (Table 1.5). Surrogate weed density in Band + plots was on average 45% less than the Standard across the Maine 2016, Maine 2017, and Vermont 2017 site-years. A final census of surrogate weed density was not collected in the Vermont 2016 site-year. While the Band + treatment resulted in fewer weeds, those surrogate weeds remaining in Band + plots were larger, having 47% greater individual biomass (g $plant^{-1}$) than surrogate weeds in Standard plots ($p = 0.018$, data not sown).

Contrary to our expected outcome, in the Maine 2016 site-year the Narrow HD and Wide + treatments outperformed the Band + treatment, having 28% and 31% fewer surrogate weeds, respectively (Table 1.5). In the Maine 2016 site-year, the average biomass of individual surrogate weeds from Wide + and Band + treatment plots did not differ ($p = 0.391$), however, surrogate weeds in Narrow HD plots were 58% smaller than those in Band + ($p = <0.001$, data not shown). These results concur with previous observations made by Kolb et al. (2010; 2012) that weeds surviving inter-row hoeing in wide-

Table 1.5. Effect of crop sowing and weed management treatment on end-of-season surrogate weed density, surrogate weed biomass, and ambient weed biomass.

Treatment	Surrogate weed density				Surrogate weed biomass				Ambient weed biomass			
	2016		2017		2016		2017		2016		2017	
	Maine[b]	Vermont[a]	Maine	Vermont[b]	Maine[b]	Vermont[b]	Maine[e]	Vermont[c]	Maine[e]	Vermont	Maine[d]	Vermont[b]
	no. m^{-2}				g m^{-2}				g m^{-2}			
Standard	6 (40)	-	26	5 (24.8)	7.2 (52.2)	11.8 (139.2)	0.8 (7.8)	6.3 (42.4)	0.9 (8.4)	37.8	0.6 (4.2)	13.7 (194.5)
Narrow HD	5 (21)	-	28	2 (5.3)	4.1 (16.6)	9.9 (97.7)	0.7 (5.9)	2.5 (10.1)	0.6 (3.1)	36.3	0.4 (3.0)	9.7 (100.0)
Wide +	4 (20)	-	18	2 (5.1)	6.3 (40.3)	10.7 (114.6)	0.7 (5.5)	2.8 (11.1)	0.7 (5.0)	21.2	0.4 (3.5)	7.6 (64.6)
Band	6 (37)	-	25	3 (9.7)	8.0 (64.7)	11.5 (132.7)	0.9 (9.4)	3.5 (15.2)	0.7 (4.2)	57.5	0.7 (5.8)	9.8 (101.7)
Band +	5 (29)	-	11	3 (10.3)	7.3 (54.1)	11.1 (123.4)	0.6 (5.6)	3.3 (14.3)	0.8 (6.0)	52.9	0.5 (3.7)	8.6 (80.0)
SE	0.1 (1.0)	-	1.7	0.3 (1.0)	0.3 (2.0)	0.4 (3.8)	0.05 (0.3)	0.3 (1.7)	0.04 (0.4)	4.0	0.04 (0.3)	0.7 (9.0)
Contrasts							P					
Band + vs. Standard	0.018	-	0.001	0.034	0.837	0.658	0.204	0.001	0.145	0.142	0.613	0.003
Band + vs. Narrow HD	0.030	-	<0.001	0.266	<0.001	0.434	0.839	0.430	0.010	0.006	0.373	0.509
Band + vs. Wide +	0.016	-	0.416	0.247	0.120	0.795	0.954	0.536	0.467	0.109	0.848	0.568
Standard vs. Narrow HD and Wide +	<0.001	-	0.230	<0.001	0.001	0.275	0.177	<0.001	<0.001	0.298	0.237	<0.001

[a]Data were not collected in the Vermont 2016 site-year.
[b]Data were square-root transformed before analysis; back-transformed means are presented in parentheses.
[c]Data were square-root (x+3) transformed before analysis; back-transformed means are presented in parentheses.
[d]Data were $\log_{10}$ transformed before analysis; back-transformed means are presented in parentheses.
[e]Data were $\log_{10}$ (x+1) transformed before analysis; back-transformed means are presented in parentheses.

row systems grow larger, having greater individual biomass; this study found the same to be true for weeds remaining in band-sown systems.

In contrast to Maine 2016 results, at the Maine site in 2017 Band + performed better than the Narrow HD treatment, resulting in 61% fewer surrogate weeds (Table 1.5). Furthermore, in support of those findings by Kolb et al. (2010; 2012), the Narrow HD and Wide + treatments reduced surrogate weed density relative to the Standard in two out of three site-years. There were no differences in surrogate weed size (g plant^{-1}) in Maine or Vermont in 2017 (data not shown).

Surrogate Weed Biomass

The Band + treatment resulted in less end-of-season surrogate weed biomass (g m^{-2}) than the Standard treatment in only one out of four site-years, Vermont 2017, when biomass was reduced by 66% (Table 1.5). Contrary to our hypothesis, the Band + treatment did not reduce surrogate weed biomass when compared with the Narrow HD or Wide + treatments, and in Maine of 2016 the Narrow HD treatment had 69% less surrogate weed biomass than the Band + treatment. In addition, the Narrow HD and Wide + treatments reduced surrogate weed biomass relative to the Standard treatment in only two out of four site-years. Inter-band hoeing (Band +) reduced surrogate weed biomass on average by 11% when compared with band-sowing alone (Band), it is therefore recommended that hoeing be performed when planting in the band-sown arrangement.

Surrogate weed biomass averaged across treatments and sites in 2016 was approximately 6.5 times greater than in 2017 (Table 1.5). Reduced surrogate weed biomass in 2017 sites-years can partially be explained by poor mustard establishment; densities were 22% and 25% less than the target 65 plants m^{-2} in Maine and Vermont, respectively (Table 1.6). Furthermore, in Maine of 2017, crop and surrogate weed planting was delayed 20 days due to precipitation when compared with the Maine 2016 site-year (Table 1.2), this delay resulted in stunted crop and surrogate weed growth. The average height of surrogate weeds in the Maine 2016 site-year was 83 cm, compared to 32 cm in 2017 (data not shown).

Table 1.6. Surrogate weed population at Maine and Vermont sites in 2016 and 2017.

2016				2017			
Maine		Vermont		Maine		Vermont	
Achieved density	Error[a]	Achieved density	Error[a]	Achieved density	Error[a]	Achieved density	Error[a]
no. m^{-2}	%	no. m^{-2}	%	no. m^{-2}	%	no. m^{-2}	%
56	-14	63	-3	51	-22	49	-25

[a]Error = (achieved density – target density) / target density. Target density for surrogate weed in all treatments was 65 no. m^{-2}.

Ambient Weed Biomass

Averaged across treatments, ambient weed biomass accounted for 13% and 25% of total weed biomass (surrogate and ambient weed biomass combined) in the Maine 2016 and 2017 site-years, respectively, and 47% and 80% in the Vermont 2016 and 2017 site-years, respectively.

Treatment effects on end-of-season ambient weed biomass (g m^{-2}) were similar to those effects on surrogate weed biomass. The only site-year that the Band + treatment reduced ambient weed biomass relative to the Standard treatment was in Vermont of 2017, when ambient weed biomass was 59% less (Table 1.5). The Band + treatment did not reduce ambient weed biomass compared to the Narrow HD or Wide + treatments in any site-year, and at Maine and Vermont sites in 2016 the Narrow HD reduced ambient weed biomass relative to Band + by 48% and 31%, respectively. Analogous to effects on surrogate weed biomass, the Narrow HD and Wide + treatments reduced ambient weed biomass compared to the Standard treatment, but only in two out of four site-years.

Timing of cultivation events likely affected treatment performance. Tine harrowing and hoeing were implemented as separate cultivation events in 2016 at both sites; 10 and 11 days passed between harrowing and hoeing at Maine and Vermont sites, respectively (Table 1.2). In 2016, timing was optimized for the performance of tine harrowing (implemented while weeds were small), resulting in delayed, suboptimal conditions for the implementation of hoeing (weeds had grown large). The efficacy of both tine harrowing and hoeing are dependent on weed size, smaller weeds are more easily controlled than larger, better established weeds (Pullen and Cowell 1997). It is likely that suboptimal timing of inter-row and band hoeing contributed to the reduced performance of the Band + treatment in 2016 (Table 1.5). At the Maine site in 2017 inter-row hoeing and then tine harrowing were performed on the same date, however, delayed planting due to spring rainfall hindered us from observing those expected improved results (see Melander et al. 2003).

Barley Yield

At the Maine site in 2016, band-sowing and hoeing did not increase barley yields (kg ha^{-1}) relative to the Standard, Narrow HD or Wide + treatments, as expected (Table 1.7). Furthermore, the yield of the Narrow HD treatment was 20% greater than Band + in the Maine 2016 site year. In the Vermont 2017 site-year, however, the Band + treatment did have greater yields than the Standard, Narrow HD, and Wide + treatments. Barley yields of the Standard, Narrow HD, and Wide + treatments were 77%, 75%, and 48% lesser than Band + yield, respectively, in Vermont of 2017. No differences in yields were detected amongst treatments in Vermont 2016 or Maine 2017 site-years. Our hypothesis therefore was not supported; we expected the Band + treatment would have greater yields than all other treatments tested, however, this only occurred in one out of four site-years.

Circumstances surrounding each site-year may have influenced experimental outcomes. At the Maine site in 2017, heavy precipitation in April and May (Table 1.3) delayed planting a total of 20 days (Table 1.2), and was followed by low precipitation in June, July and August. Delayed planting in combination with little rainfall are likely responsible for the reduced weed biomass and barley yields observed in Maine of 2017. In the Vermont 2017 site-year, hoeing and harrowing were performed on the same date, but Wide + and Band + treatments did not receive POST tine harrowing (Table 1.1). In the Vermont 2017 site-year barley yield was elevated in the Band + treatment when compared with the Standard, Narrow HD, and Wide + treatments (Table 1.7), and surrogate and ambient weed biomass were reduced compared to the Standard. This suggests that inter-row hoeing alone may provide sufficient weed control.

Table 1.7. Effect of crop sowing and weed management treatment on barley yield.

Treatment	Barley yield			
	2016		2017	
	Maine	Vermont	Maine	Vermont
	kg ha^{-1}			
Standard	938	659	504	256
Narrow HD	1052	658	522	273
Wide+	935	553	513	567
Band	832	652	445	732
Band +	878	609	502	1099
SE	22	35	23	96
Contrasts	P			
Band + vs. Standard	0.284	0.491	0.964	0.003
Band + vs. Narrow HD	0.005	0.500	0.703	0.003
Band + vs. Wide +	0.306	0.438	0.833	0.033
Standard vs. Narrow HD and Wide +	0.248	0.395	0.772	0.409

Barley Quality

In agreement with Huhtaplo (1986), who observed greater thousand kernel weights (g) when band-sowing cereals versus row-planting, the Band + treatment resulted in a barley crop with 7% greater thousand kernel weight than the Standard treatment in Vermont of 2016, and 3% and 12% greater the Narrow HD treatment in Maine and Vermont 2016 site-years, respectively (Table 1.8). Thousand kernel weight was not determined for Vermont 2017 samples.

The American Malting Barley Association (AMBA) classifies ideal two-row malting barley as having greater than 90% plump kernels (AMBA 2018). All treatments exceeded 90% plump kernels in 2016; at the Maine site the Narrow HD treatment resulted in fewer plump kernels. In 2017, no treatments exceeded 90% plump kernels; in the Maine 2017 site-year the Band + treatment resulted in 6.1%, 6.6% and 5% more plump kernels than the Standard, Narrow HD, and Band treatments, respectively. Results suggest that band-sowing with inter-row hoeing may improve thousand kernel weight and plump kernel grain quality parameters.

The AMBA also classifies ideal two-row malting barley as having less than or equal to 13% protein content (AMBA 2018), and in this experiment protein never exceeded 13% (Table 1.8). Test weight (lb. bu^{-1}), germination energy (%), and DON mycotoxin levels (ppm) were not affected by treatment. It is notable, however, that grains possessing DON levels in excess of 1 ppm are considered unfit for human consumption by the U.S. Food and Drug Administration (USFDA 2010). In the Vermont 2017 site-year the Standard, Narrow HD, and Band treatments had DON levels of 1.0 ppm, and barley from the Band + treatment had an average DON level of 1.1 ppm.

Conclusions

Going forward, field experiments evaluating band-sowing and hoeing would benefit from introducing tine-harrowing as a separate treatment. Given ideal conditions, tine-harrow efficacy can be very high (Rasmussen 2004; Lundkvist 2009*;* Cirujeda et al. 2003); split-plots, for example, would have allowed for analysis with and without the effect of harrowing. It should also be noted that a single seeding rate, band width, and inter-band spacing were tested in this experiment. It is likely that further optimization of the band-sowing strategy may be achieved by altering these parameters. Leveraging an argument similar to that of Fischer and Miles (1973), Speelman (1975) contended that crop distribution is improved as the mean distance between nearest neighbors increases and variation decreases, in other words, as the crop arrangement becomes more uniform and equidistant. Speelman simulated the effects of band width, seeding rate, and distribution on grain yield, concluding that the band-sowing was a superior arrangement to that of row-planting, and that those improvements were realized at narrow band width of 5 cm. Speelman also performed field trials in winter wheat that compared band-sowing, broadcast sowing, and row-planting. Band-sown yields were

Table 1.8. Effect of crop sowing and weed management treatment on barley test weight, thousand kernel weight, plump kernels, germination energy, grain protein and Deoxynivalenol mycotoxin (DON).

Treatment	Test weight				Thousand kernel weight				Plump kernels			
	2016		2017		2016[b]		2017		2016[b]		2017	
	Maine[a]	Vermont[b]	Maine[a]	Vermont[b]	Maine	Vermont	Maine[b]	Vermont[c]	Maine[d]	Vermont	Maine[a]	Vermont[b]
	lb bu^{-1}				g				%			
Standard	51.3	42.1	46.5	45.0	44.5 bc	45.3 bc	35.6	-	96.3 a	94.1	70.7 bc	85.5
Narrow HD	51.0	39.9	45.7	42.5	43.9 c	43.4 c	34.7	-	95.0 b	91.2	70.2 c	85.6
Wide +	51.2	38.9	46.5	44.2	45.9 a	46.3 ab	37.6	-	96.3 a	92.8	74.4 ab	86.8
Band	51.5	40.4	46.6	44.3	45.4 ab	48.1 a	35.4	-	96.6 a	95.2	71.8 bc	89.5
Band +	51.3	41.5	47.0	43.4	45.3 ab	48.5 a	37.8	-	96.8 a	94.2	76.8 a	87.8
SE	0.1	1.3	0.2	0.4	0.2	0.5	0.6	-	0.2	0.5	0.9	1.0
ANOVA					P							
Treatment	0.540	0.847	0.136	0.322	0.025	0.003	0.102	-	0.002	0.069	0.001	0.227

Treatment	Germination energy				Grain protein				DON			
	2016[d]		2017		2016[b]		2017		2016		2017	
	Maine[a]	Vermont[b]	Maine[a]	Vermont[b]	Maine	Vermont	Maine[b]	Vermont[a]	Maine[e]	Vermont[b]	Maine[e]	Vermont[b]
	%				%				ppm			
Standard	99.5	96.3	95.8	97.5	7.9	10.5	8.4	9.5 ab		0.6		1.0
Narrow HD	98.5	96.5	96.2	97.8	8.0	10.1	8.1	9.2 abc		0.5		1.0
Wide +	98.9	93.5	94.3	97.8	8.3	10.5	8.6	9.2 abc	<0.1	0.5	<0.1	0.7
Band	99.5	96.8	96.4	98.5	7.9	10.4	8.3	9.1 c		0.6		1.0
Band +	99.2	90.0	94.8	98.3	7.9	10.7	8.3	9.7 a		0.4		1.1
SE	0.1	1.3	0.4	0.2	0.1	0.1	0.1	0.1	-	0.1	-	0.1
ANOVA					P							
Treatment	0.185	0.489	0.637	0.611	0.389	0.850	0.498	0.038	-	0.597	-	0.620

[a]Data were analyzed with the Kruskal-Wallis test; the Wilcoxon signed-rank test was used to perform means comparisons.
[b]Data were analyzed with ANOVA; Fischer's protected LSD was used to perform means comparisons.
[c]Data were not collected in the Vermont 2017 site-year.
[d]Data were arcsine transformed before analysis; non-transformed means are presented.
[e]DON (ppm) was measured as an aggregate sample across all treatment plots in the Maine 2016 and Maine 2017 site-years.

greatest, but not significantly different from those attained by other crop arrangements. In agreement with Spellman's models, Huhtaplo (1986) found that planting in narrow, 7 cm bands with 5.5 cm between crop bands increased barley yields by 1% when compared with a row-planted treatment. Sowing in narrow, 3 to 4 cm wide bands may be achieved by altering a standard double-disc grain drill (Heege 1993). This method may provide a low-cost option for growers to access the benefits of band-sowing using existing equipment.

In conclusion, results from the four site-years of this experiment found that band-sowing with inter-band hoeing is not consistently superior to other weed management strategies. This can partially be explained by suboptimal implementation of inter-row and inter-band hoeing in 2016, and adverse weather conditions in 2017. However, based on a strong theoretical rationale, its observed performance in Northern Europe, and farmer testimonial, band-sowing with hoeing remains a compelling system worthy of further investigation. Additionally, in separate experiments performed by McCollough and Gallandt (described in *Chapter 2*) in 2016 and 2017 comparing band-sowing with the region's standard cropping practice for four test crops (spring wheat, oats, flax, and field peas), band-sowing reduced weed biomass in three out of four crops by 40 to 72% in 2016, and in all crops by 5 to 63% in 2017. Nevertheless, further experimentation into the optimization of band-sowing should be conducted prior to endorsing its use for organic cereal growers operating in the Northeast region of the United States.

CHAPTER 2

BAND-SOWING WITH HOEING FOR IMPROVED WEED MANAGEMENT IN ORGANIC WHEAT, OAT, FIELD PEA, AND FLAX

Introduction

Increased demand and attractive market prices for locally produced, organic grains have prompted farmers to increase production in the Northeastern United States, however, weed management remains a challenging production problem. Weeds reduce grain yield and quality, interfere with harvest, and may increase foliar disease problems (Oerke 2006; Jabran et al. 2017).

In organic farming, a diverse crop rotation can be leveraged to increase crop yields, improve soil quality, while contributing to the management of weeds, pests, and diseases. Ideally, sowing and physical weed control practices can be developed for multiple grain crops to encourage diversification without requirements for additional equipment. Leguminous cash crops such as field pea (*Pisum sativum* L.) are often included in rotation with cereals because of their nitrogen-fixing ability and associated low-input requirements (Stagnari et al. 2017). Field pea also improved the yields of subsequent cereal crops (Jensen et al. 2004; Angus et al. 2015; Stagnari et al. 2017). Flax (*Linum usitatissimum* L.) is another cash crop that if properly managed may improve the yield of a subsequent cereal crop (Angus et al. 2015). In the Northeastern United States, there has been interest in growing oilseed flax as supplementary feed for dairy cows (Hafla et al. 2017), however, niche marketing opportunities may also exist for food and fiber (Sing et al. 2011). Additionally, both field pea and flax serve as break crops from diseases affecting small grains (Angus et al. 2015). The foremost challenge associated with organic production of field pea and flax, however, is also the management of weeds (R Kersbergen, personal communication). To effectively manage weeds at the farm-scale, it is essential that weeds be adequately controlled in all crops within a rotation; thus, eliminating negative legacy effects associated with a weedy crop, including contributions to the weed seed bank (Zentner and Campbell 1988; Bagavathiannan and Norsworthy 2012; Brown and Gallandt 2018).

In northern New England, organic field pea, flax, and small grains are typically planted using a grain drill, in rows spaced 15 to 20 cm apart. Weed management relies on PRE and/or POST tine harrowing when weather and field conditions permit. While tine-harrows can be very effective and result in improved crop yields, there are considerable challenges associated with reliance on tine harrowing for weed control, specifically low and variable efficacy (Gallandt et al., 2018).

A promising alternative to typical grain drills and tine harrowing is band-sowing with inter-band hoeing plus tine harrowing. Hoeing in cereals was first adopted by organic cereal farmers in Northern Europe who were experiencing intractable perennial weed problems. Band-sowing offers both physical and cultural methods of weed control. Instead of planting in rows, shoe-type openers broadcast the crop within 5 to 20 cm bands. Altering crop spatial arrangement from aggregated single-line rows, to a more uniform distribution in a band reduces intraspecific competition, and in theory, increases interspecific competition (Fischer and Miles 1973; Speelman 1975). Indeed, more uniform sowing improved weed suppression and increased yields in spring wheat (*Triticum aestivum* L.) (Weiner et al. 2001; Olsen et al. 2005b) and oat (*Avena sativa* L.) (Regnier and Bakelana 1995). The few studies that have compared band-sowing with row-planting have observed increased yields and weed control in cereal crops (Speelman 1975; Andersson 1986; Huhtapalo 1986; Heege 1993). Weeds in the inter-band zone are controlled by hoeing with sweeps. Compared to tine harrowing, sweeps offer greater weed control efficacy across a wider range of soil conditions, weed species, and weed sizes (Pullen and Cowell 1997; Melander et al. 2003).

Our objectives were to evaluate the effects of band-sowing with inter-band hoeing on weed control and yield of several grain crops likely to be grown in rotation by farmers in northern New England, USA. Test crops included spring wheat, oat, field pea, and flax. We hypothesized that band-sowing and hoeing would provide superior weed control and elevated yields when compared with the region's standard practice.

Materials and Methods

Site Characteristics, History, and Preparation

Field experiments were performed in 2016 and 2017 at the Rogers Farm Forage and Crop Research Facility in Old Town, Maine (44.93°N, 68.70°W). Experiments were conducted in fields consisting of a Nicholville very fine sandy loam in 2016, and a Pushaw-Boothbay complex soil type in 2017. Fields were managed uniformly prior to establishing the 2016 experiment; oats were planted on April 26, 2015, then mowed and incorporated; corn (*Zea mays* L.) was planted on July 31, 2015. The experiment was split into two fields in 2017, blocks 1 and 2 were planted in Field J, and blocks 3 and 4 were planted in Field G. In 2016, Field J was planted to field peas and was not treated with any herbicide; Field G was planted to potatoes (*Solanum tuberosum* L.) and was treated with metribuzin (Sencor 75 DF®, 3.3 g ai L^{-1}, Bayer CropScience Inc., 100 Bayer Blvd., Whippany, New Jersey, United States), s-metolanchlor (Charger Max®, 7.2 g ai L^{-1}, WinField United, Arden Hills, Minnesota, United States), and rimsulfuron (Matrix® SG, 1.5 g ai L^{-1}, DuPont, Wilmington, Delaware, United States). Fields used in the 2016 experiment were USDA certified organic while fields used in 2017 were not certified, however, in both experimental years, fields were managed organically.

Soil fertility was amended with solid dairy manure based on soil test results to attain 73 kg ha^{-1} of plant-available nitrogen. Within 12 hours prior to planting each crop, seedbeds were prepared using a Perfecta® Field Cultivator (Unverferth Manufacturing Company Inc., Kalida, Ohio, United States).

Treatments

Test crops included hard red spring wheat (*Triticum aestivum* L. 'Glenn'), oats (*Avena sativa* L. 'Colt'), oilseed flax (*Linum usitatissimum* L. 'Prairie Thunder'), and field peas (*Pisum sativum* L. 'Jetset'). Field peas were inoculated with N-Dure® Pea/Vetch/Lentil *(Rhizobium leguminosarum biovar viceae*, Verdesian Life Sciences, Cary, NC, United States) before planting. Two treatments were implemented for each crop: our region's standard cropping practice (Standard), and band-sown with inter-band hoeing (Band +). Standard and Band + treatments were planted at the same target density for each crop: wheat at 400 plants m^{-2}, oats at 325 plants m^{-2}, flax at 800 plants m^{-2}, and field peas at 100 plants m^{-2}. The Standard treatment was sown in 16.5 cm rows using a grain drill with double-disc openers (H & N Equipment, Colwich, KS, United States). The Band + treatment was sown in 12.7 cm bands with 15.2 cm between planted crop bands (27.9 cm on-center spacing). Band-sown plots were planted using a Vicon air seeder (Kverneland Group, Klepp, Norway) with Dutch Openers (Dutch Industries Ltd., Pilot Butte, SK, Canada). Condiment mustard (*Sinapsis alba* L. 'Ida Gold') was planted as a surrogate weed in all experimental plots. Mustard was sown immediately after each crop at a rate of 65 plants m^{-2} using a Brillion Sure Stand Grass Seeder (Landoll Corporation, Marysville, KS, United States).

Standard and Band + treatments received POST tine harrowing when conditions permitted. Harrowing was performed with a Williams Tool System spring tine harrow (Market Farm Implement, Friedens, Pennsylvania, United States) with 6 mm tines. The Band + treatment also received inter-band hoeing using a Schmotzer cultivator (Maschinenfabrik Schmotzer GmbH, Windsheim, Germany), with 12.7 cm sweeps. Inter-band hoeing was either performed once or twice depending upon field and weather conditions.

Experimental Design

The experimental design was a randomized complete block design with four blocks. Since growth rate and canopy architecture vary among those crops tested, Standard and Band + treatments of each crop were planted in adjacent plots within each block to ensure uniform competition and protect against edge effects. Guard plots planted to spring barley (*Hordeum vulgar* L. 'Newdale') were established throughout the experiment on either side of the paired plots.

Data Collection

Prior to harvest, plant biomass was cut at a height of 13 mm above the soil surface in three 0.25 m^{-2} quadrats placed randomly in the central area of each plot. The crop, surrogate weeds, and ambient weeds were separated, and a census of surrogate weeds was performed. Ambient weeds were further divided into three categories: most abundant weed species, second most abundant weed species, and all other ambient weeds. Separated plant matter was then dried for a minimum of 7 days at 49°C and weighed.

Wheat, oat, and field pea were harvested with a Wintersteiger Classic plot combine (Wintersteiger Inc., Salt Lake City, Utah, United States). Flax was hand harvested from four randomly place 0.25 m^{-2} quadrats and threshed by hand. Grain was cleaned using a Clipper Model 400 Office Tester and Cleaner (Seedburo Equipment Co., Des Plaines, Illinois, United States). Grain moisture of wheat, oat, and field pea crops was measured with a DICKEY-john GAC 2100 Agri (DICKEY-john, Auburn, Illinois, United States); flax moisture was determined using oven drying methods outlined by the National Institute of Standards and Technology (Lee and Olson 2017). Yields were adjusted to a standard moisture content of 13.5%.

Analysis

JMP® 10.0.2 software (SAS Institute Inc., Cary, North Carolina, United States) was used to perform statistical analyses. Due to differences among the cultivation events performed in the Band + treatment across experimental years (Table 2.1, 2.2), and significant treatment by year effects ($p = <0.05$), data from 2016 and 2017 were analyzed separately. Pooled t-tests were used to compare means. Shapiro-Wilk's and two-tailed F-tests were performed to confirm that data met the assumptions of a normal distribution and homogeneity of variance (α=0.05). Transformations, including $\log_{10}$, $\log_{10}$ (x+1), square-root and Box-Cox were used if data did not comply with assumptions. When treatment variables were compared, pooled t-tests resulted in numerous instances where p-values fell between

0.05 and 0.10; after reviewing results, it was determined that a significance level of 0.10 would be used to characterize differences among groups.

Table 2.1. Cultivation events performed in 2016 and 2017.

Year	Site	Treatment	Cultivation events		
			POST tine harrowing	First inter-band cultivation	Second inter-band cultivation
				no.	
2016	Wheat	Standard	1	-	-
		Band +	0	1	1
	Oat	Standard	1	-	-
		Band +	0	1	1
	Field Pea	Standard	1	-	-
		Band +	0	1	1
	Flax	Standard	1	-	-
		Band +	0	1	1
2017	Wheat	Standard	1	-	-
		Band +	1[a]	1[a]	1
	Oat	Standard	1	-	-
		Band +	1[a]	1[a]	1
	Field Pea	Standard	1	-	-
		Band +	1[a]	1[a]	0
	Flax	Standard	1	-	-
		Band +	1[a]	1[a]	0

[a]In the Maine 2017 site-year, the 1st inter-band cultivation event and POST harrowing were performed in sequence.

Table 2.2. Summary of dates and crop growth stages that field operations were performed.

Field operation	Wheat		Oat		Field Pea		Flax	
	Date	Stage[a]	Date	Stage[a]	Date	Stage[b]	Date	Stage[b]
2016								
Fertilize	May 16		May 16		May 16		May 16	
Sow crop and surrogate weed	May 18		May 18		May 18		May 18	
POST tine harrowing	June 9	13, 21	June 9	13, 22	June 9	15-17	June 9	13-15
First inter-band cultivation	June 9	13, 21	June 9	13, 22	June 9	15-17	June 9	13-15
Second inter-band cultivation	June 16	14, 22	June 16	14, 22	June 16	19	June 16	17-19
Peak biomass	July 29	85	July 27	85	July 26-27	79	July 27	85
Grain harvest	August 23		August 23		August 23		August 23-24	
2017								
Fertilize	May 19		May 19		May 19		May 19	
Sow crop and surrogate weed	May 19		May 19		May 19		May 19	
POST tine harrowing	June 14	13, 21-23	June 8	12	June 14	14-16	June 22	19
First inter-band cultivation	June 14	13, 21-23	June 8	12	June 14	14-16	June 22	19
Second inter-band cultivation	June 29	15, 21-24	June 14	12, 21	-		-	
Peak biomass	July 30	87	July 31	87	August 1	88	August 8	85
Grain harvest	August 25		August 15		August 15		August 31	

[a]Wheat and oat growth stages are described using Zadok et al. (1974) decimal code for cereals.
[b]Field pea and flax growth stages are described using Lancashire et al. (1991) BBCH decimal code.

Results and Discussion

Weather

Experiments were conducted in May through August, during which time total precipitation was 18 mm less than the 30-year average in 2016, and 59 mm less in 2017 (Table 2.3). In 2016, rainfall during the months of May, June, and August was 23% below average. July of 2016 was quite wet however, precipitation was 57% greater than average. The 2017 site-year started out wet, we received 36% greater than average rainfall in May, whereas in remaining months rainfall was 37% below average.

Table 2.3. Total rainfall during the months of May – August in 2016 and 2017 compared with 30-year means from 1988 to 2017.

Month	Total rainfall		
	2016	2017	30-year mean
		mm	
May	77	124	91
June	65	68	100
July	119	47	76
August	62	43	74
Total	323	282	341

Surrogate Weed Density

In 2016, band-sowing with hoeing and harrowing reduced surrogate weed density relative to the Standard treatment by 32% in wheat, by 49% in oat, and by 33% in field pea (Table 2.4). In 2017, the Band + treatment reduced surrogate weed density in all crops tested; averaged across crops, surrogate weed density was 38% less than the Standard treatment.

As weeds grow larger they become more difficult to manage using physical methods of control (Pullen and Cowell 1997) including tine harrows (Baerveldt and Ascard 1999; Kurstjens et al. 2000; Lundkvist 2009) and sweeps (Melander et al. 2003; Johansson 1998). Band + was designed to receive POST tine harrowing in addition to inter-band hoeing. In 2016, however, we refrained from harrowing so

Table 2.4. Effect of crop sowing and weed management treatment on end-of-season surrogate weed density, surrogate weed biomass, and ambient weed biomass.

	Surrogate weed density				Surrogate weed biomass				Ambient weed biomass			
	2016				2016				2016			
Treatment	Wheat	Oat[a]	Field Pea[a]	Flax	Wheat	Oat	Field Pea	Flax	Wheat[b]	Oat[a]	Field Pea	Flax
	no. m^{-2}				g m^{-2}				g m^{-2}			
Standard	29.0	1.5 (32.2)	1.5 (31.6)	21.7	5.3 (28.6)	7.7 (61.0)	9.1 (94.6)	8.6 (76.4)	8.4 (79.3)	1.8 (73.6)	195.1	214.5
Band +	19.7	1.2 (16.3)	1.3 (21.1)	25.7	4.0 (16.5)	3.9 (16.7)	6.7 (56.3)	10.3 (108.5)	6.4 (49.5)	1.7 (59.4)	134.5	262.8
SE	2.5	0.1 (2.3)	0.1 (2.0)	1.7	0.5 (1.5)	0.6 (5.6)	1.0 (12.1)	0.6 (6.6)	0.7 (10.3)	0.04 (6.0)	23.8	18.1
P > t	0.031	<0.001	0.061	0.865	0.095	<0.001	0.054	0.080	0.007	0.059	0.006	0.057
Treatment	2017				2017				2017			
	Wheat	Oat	Field Pea	Flax	Wheat	Oat	Field Pea	Flax	Wheat	Oat[b]	Field Pea	Flax[b]
Standard	50.7	50.3	74.7	80.7	4.6 (21.9)	1.5 (33.8)	13.7 (192.3)	203.2	8.9	2.6 (6.9)	39.9	7.8 (61.1)
Band +	28.3	33.0	51.0	48.0	2.8 (8.1)	1.3 (21.9)	13.3 (183.6)	118.2	5.8	2.2 (5.0)	43.3	6.7 (46.2)
SE	3.5	4.0	5.2	6.5	0.3 (1.8)	0.1 (1.7)	0.7 (12.3)	16.5	1.1	0.1 (0.3)	4.0	0.3 (3.6)
P > t	<0.001	0.009	<0.001	<0.001	<0.001	0.075	0.386	0.003	0.017	0.088	0.313	0.022

[a]Data were $\log_{10}$ transformed before analysis; back-transformed means are presented in parentheses.
[b]Data were square-root transformed before analysis; back-transformed means are presented in parentheses.

that inter-band hoeing could be performed when conditions were ideal, and weeds were small. In 2017 hoeing and harrowing were performed on the same date, in sequence (Table 2.1, 2.2); it is likely that the improved performance of the Band + treatment in 2017 is due in part to this change. Melander et al. (2001) found that combining inter-row hoeing with tine harrowing improved efficacy on average by 30% when compared with hoeing alone.

Field peas were not hoed a second time in 2017 due to canopy closure between bands; hoeing would have caused considerable crop damage. Flax only received one hoeing in 2017 as well because the first inter-band cultivation was delayed due to the crop's slow growth rate (Table 2.1, 2.2).

Surrogate and Ambient Weed Biomass

In 2016, the Band + treatment decreased surrogate weed biomass (g m^{-2}) compared to the Standard by 42% in wheat, 72% in oat, and 40% in field pea; in flax, however, surrogate weed biomass was 42% greater with band-sowing (Table 2.4). In 2017, the Band + treatment reduced surrogate weed biomass relative to the regional standard by 63% in wheat, 35% in oat, and 42% in flax.

Ambient weeds accounted for 66% and 25% of total weed biomass (surrogate and ambient weed biomass combined) in 2016 and 2017, respectively. Averaged across treatments, makeup of ambient weed biomass samples was: 32% redroot pigweed (*Amaranthus retroflexus* L.), 56% common lambsquarters (*Chenopodium album* L.), and 12% other ambient weeds in 2016; 36% *C. album*, 8% yellow nutsedge (*Cyperus esculentus* L.), and 56% other in 2017 (data not shown).

Comparable to observed effects on surrogate weeds in 2016, ambient weed biomass (g m^{-2}) was reduced by band-sowing in wheat, oat, and field pea by 38%, 19%, and 31%, respectively; in flax, biomass of ambient weeds was 23% greater in the Band + treatment than in the Standard (Table 2.4). In 2017, the Band + treatment resulted in reductions of ambient weed biomass by 35% in wheat, 28% in oat, and 24% in flax.

Surrogate weed density, surrogate weed biomass, and ambient weed biomass results are supportive of our hypothesis that band-sowing in combination with inter-band hoeing would provide superior weed control to the region's standard practice. In the first year of the experiment band-sowing reduced surrogate weed density, surrogate weed biomass, and ambient weed biomass compared to the region's standard practice in three out of four crops; in year two, band-sowing with hoeing reduced surrogate weed density in all crops, and reduced surrogate and ambient weed biomass in three of four crops (Table 2.4).

Yield

Yield of wheat, oat, and field pea were on average 24% greater in 2016 than 2017, whereas flax yield was 3% greater in 2017 (Table 2.5). Below average rainfall for the months of June, July and August of 2017 likely contributed to reduced crop yields in this year (Table 2.3).

Yield response to standard and band-sowing management strategies varied among test crops and experimental years. In 2016, oat yield was positively affected by band-sowing with hoeing, Band + yields were greater than Standard treatment yields by 6% (Table 2.5). Contrary to our hypothesized results, the Standard field pea yield was 55% greater than in the Band + treatment in 2017. No differences in yield were detected either year in flax and wheat, nor in field pea and oat in 2016 and 2017, respectively.

Reduced yields in 2017 field pea are likely due in part to poor timing of inter-band cultivation. Experiments performed by Stanley et al. (2018) in a weed-free environment found that hoeing could reduce the yield of field pea; two and three inter-row hoeing events reduced yields by 14 to 31% and 19 to 31%, respectively. Stanley et al. (2018) also determined that field pea yields were negatively correlated with delayed inter-row cultivation past the BBCH growth stage 13.5 (Lancashire et al. 1991). We performed inter-band hoeing twice in 2016, when the crop was between growth stages 15 and 17, and again at stage 19 (Table 2.1, 2.2). In 2017, inter-band hoeing was performed once, when the crop was between growth stages 14 and 16. To improve performance in field pea, future studies on band-sowing with cultivation should adhere to those recommendations of Stanley et al. (2018); inter-band cultivation should be performed once, one to two weeks after crop emergence (Harker et al. 2001), when the crop is at BBCH growth stage 13 or 14.

Table 2.5. Effect of crop sowing and weed management strategy on crop yield.

Treatment	Crop yield							
	2016				2017			
	Wheat	Oat	Field Pea	Flax	Wheat	Oat	Field Pea	Flax
	kg ha^{-1}							
Standard	390	623	435	121	291	463	418	127
Band +	427	661	374	103	284	475	269	105
SE	14.1	13.7	69.5	6.4	15.6	17.3	41.8	26.5
P > t	0.109	0.031	0.328	0.166	0.329	0.416	0.007	0.102

[a]To meet the assumptions of the pooled t-test, data were Box-Cox transformed before analysis; untransformed means are presented.

In summary, oats and wheat responded best to band-sowing with hoeing, while field pea and flax results were variable. Oat yields were increased compared to the Standard by band-sowing in 2016 (Table 2.5). Surrogate weed density, and the biomass of surrogate and ambient weeds was reduced in oat both years by the Band + treatment (Table 2.4). Wheat yields were not affected by treatment, however, in both years, surrogate weed density, surrogate weed biomass, and ambient weed biomass were reduced by band-sowing. Reductions in weed biomass will have a corresponding effect on weed seed rain, thus contributing to improving longer-term weed management.

Small grain crops including wheat and oats are considered highly competitive species (van Heemst 1985). According to Blackshaw et al. (2002), competitive ability of our test crops would have the following rank order: oat > wheat > field pea > flax. Because band-sowing relies on crop-weed competition for the successful suppression of weeds in the inter-band zone, cereal crops are likely best suited for this strategy, and results from this experiment support this notion. However, experiments performed by McCollough et al. (described in *Chapter 1*) comparing band-sowing with hoeing to standard and alternative weed management practices in spring barley were inconsistent. Only summer annuals were tested in this experiment, however, the inclusion of crops with differing life cycles can improve the weed suppressive effects of a crop rotation (Smith 2006); therefore, we suggest that band-sowing and hoeing be assessed in winter grains in future research.

Overall, results from this study indicate that band-sowing with inter-band hoeing is a promising weed management strategy for growing multiple grain crops. However, across those crops studied, yields were not consistently improved by band-sowing; significantly increased yields were only observed in oat in one year. It is important to note that for each crop a single seeding rate, band width, and inter-band width were tested; before recommending band-sowing to organic grain growers in northern New England, USA, we suggest that research be performed to evaluate the effects and interactions of these variables to optimize weed suppression and yield outcomes.

REFERENCES

[AMBA] American Malting Barley Association, Inc. (2018) Malting Barley Breeding Guidelines Ideal Commercial Malt Criteria. <http://ambainc.org/media/AMBA_PDFs/Pubs/Malting_Barley_Breeding_Guidelines_June_2018.pdf> Accessed: July 10, 2018

Andersson B (1986) Influence of crop density and spacing on weed competition and grain yield in wheat and barley. Pages 121-128 *in* Proceedings European Weed Research Society Symposium 1986, Economic Weed Control. Hohenheim, Germany

Angus JF, Kirkegaard JA, Hunt JR, Ryan MH, Ohlander L, Peoples MB (2015) Break crops and rotations for wheat. *Crop and Pasture Science* 66:523-552

[ASBC] American Society of Brewing Chemists (1958) Barley-3 Germination Energy. *in* Methods of Analysis. St. Paul, MN: ASBC

[ASBC] American Society of Brewing Chemists (2011) Malt-8 Protein (N X 6.25). *in* Methods of Analysis. St. Paul, MN: ASBC

Baerveldt S, Ascard J (1999) Effect of soil covering on weeds. *Biological Agriculture and Horticulture* 17:101-111

Bagavathiannan MV, Norsworthy JK (2012) Late-season seed production in arable weed communities: management implications. *Weed Science* 60:325-334

Blackshaw RE, O'Donovan JT, Harker KN, Li X (2002) Beyond herbicides: new approaches to managing weeds. Pages 305-312 *in* Proceedings of the International Conference on Environmentally Sustainable Agriculture for Dry Areas. Lethbridge, AB, Canada

Brown B, Gallandt ER (2018) A systems comparison of contrasting organic weed management strategies. *Weed Science* 66:109-120

Cheam AH, Storrie AM, Koetz EA, Holding DJ, Bower AJ, Barker JA (2008) Managing wild radish and other brassicaceous weeds in Australian cropping systems. Adelaide, Austrailia: Grains Research and Development Corporation, Cooperative Research Centre for Weed Management Systems. 88 p

Cirujeda A, Melander B, Rasmussen K, Rasmussen IA (2003) Relationship between speed, soil movement into the cereal row and intra-row weed control efficacy by weed harrowing. *Weed Research* 43:285-296

Doll H (1997) The ability of barley to compete with weeds. *Biological Agriculture and Horticulture* 14:43-51

Fischer RA, Miles RE (1973) The role of spatial pattern in the competition between crop plants and weeds. A theoretical analysis. *Mathematical Biosciences* 18:335-350

Gallandt ER, Brainard D, Brown B (2018) Developments in physical weed control. Pages 1-23 *in* Zimdahl RL, ed. Integrated weed management for sustainable agriculture. Cambridge, United Kingdom: Burleigh Dodds Science Publishing

Hafla AN, Soder KJ, Brito AF, Kersbergen R, Benson R, Darby H, Rubano MD, Dillard SL, Kraft J, Reis SF (2017) Winter supplementation of ground whole flaxseed impacts milk fatty acid composition on organic dairy farms in the Northeastern United States. *Journal of Animal Science* 95:142-143

Harker NK, Blackshaw RE, Clayton GW (2001) Timing weed removal in field pea (Pisum sativum). *Weed Technology* 15:277-283

Heege HJ (1993) Seeding methods performance for cereals, rape, and beans. *Transactions of the ASAE* 36:653-661

van Heemst HDJ (1985) The influence of weed competition on crop yield. *Agricultural Systems* 18:81-93

Huhtapalo Å (1986) Establishment of the small grain crop by band sowing (wing coulters) or drilling (shoe coulters). *Soil and Tillage Research* 8:336-337

Jabran K, Mahmood K, Melander B, Bajwa AA, Kudsk P (2017) Weed dynamics and management in wheat. Pages 97-166 *in* Sparks D, eds. Advances in Agronomy, Volume 145. New York: Academic Press

Jensen CR, Joernsgaard B, Andersen MN, Christiansen JL, Morgensen VO, Friis P, Petersen CT (2004) The effect of lupins as compared with peas and oats on the yield of the subsequent winter barley crop. *European Journal of Agronomy* 20:405-418

Johansson D (1988) Radhackning med och utan efterredskap i stråsäd (Row hoeing in cereals with and without tools behind. Final report for field experiments 1995-1997. With English summary). Uppsala, Sweden: Sveriges Lantbruksuniversitet. 48 p

Kolb LN, Gallandt ER (2012) Weed management in organic cereals: advances and opportunities. *Organic Agriculture* 2:23-42

Kolb LN, Gallandt ER, Mallory EB (2012) Impact of spring wheat planting density, row spacing, and mechanical weed control on yield, grain protein, and economic return in Maine. *Weed Science* 60:244-253

Kolb LN, Gallandt ER, Molloy T (2010) Improving weed management in organic spring barley: physical weed control vs. interspecific competition. *Weed Research* 50:597-605

Kurstjens DAG, Kropff MJ (2001) The impact of uprooting and soil-covering on the effectiveness of weed harrowing. *Weed Research* 41:211-228

Kurstjens DAG, Perdok UD, Goense D (2000) Selective uprooting by weed harrowing on sandy soils. *Weed Research* 40:431-447

Lancashire PD, Bleiholder H, Boom TVD, Langelüddeke P, Stauss R, Webber E, Witzenberger A (1991) A uniform decimal code for growth stages of crops and weeds. *Annals of Applied Biology* 119:561-601

Lee GD, Olson D (2017) Examination of Grain Moisture Meters Using Air-Oven Reference Method Transfer Standards, Handbook 159, 2017 Edition. Washington, DC: U.S. Department of Commerce, National Institute of Standards and Technology (NIST). 80 p

Lundkvist A (2009) Effects of pre- and post-emergence weed harrowing on annual weeds in peas and spring cereals. *Weed Research* 49:409-416

Melander B, Cirujeda A, Jørgensen MH (2003) Effects of inter-row hoeing and fertilizer placement on weed growth and yield of winter wheat. *Weed Research* 43:428-423

Melander B, Rasmussen IA, Bárberi P (2005) Integrating physical and cultural methods of weed control: examples from European research. *Weed Science* 53:361-381

Melander B, Rasmussen K, Rasmussen IA (2001) Row hoeing followed by weed harrowing in winter cereals in spring under the influence of different cropping factors. Pages 211-215 *in* Proceedings of the 18th Danish Plant Protection Conference. Nyborg, Denmark: Danish Institute of Agricultural Sciences

Oerke EC (2006) Crop losses to pests. *Journal of Agricultural Science* 144:31-43

Olsen J, Kristensen L, Weiner J (2005a) Effects of density and spatial pattern of winter wheat on suppression of different weed species. *Weed Science* 53:690-694

Olsen J, Kristensen L, Weiner J, Griepentrog HW (2005b) Increased density and spatial uniformity increase weed suppression by spring wheat. *Weed Research* 45:316-321

Pullen DWM, Cowell PA (1997) An evaluation of the performance of mechanical weeding mechanisms for use in high speed inter-row weeding of arable crops. *Journal of Agricultural Engineering Research* 67:27-34

Rasmussen IA (2004) The effect of sowing date, stale seedbed, row width and mechanical weed control on weeds and yields of organic winter wheat. *Weed Research* 44:12-20

Rasmussen J (1991) A model for prediction of yield response in weed harrowing. *Weed Research* 31:401-408

Rasmussen J, Nielsen HH, Gundersen H (2009) Tolerance and selectivity of cereal species and cultivars to postemergence weed harrowing. *Weed Science* 57:338-345

Regnier EE, Bakelana KB (1995) Crop planting pattern effects on early growth and canopy shape of cultivated and wild oats (Avena fatua). *Weed Science* 43:88-94

Singh KK, Mridula D, Rehal J, Barnwal P (2011) Flaxseed: a potential source of food, feed, and fiber. *Critical Reviews in Food Science and Nutrition* 51:210-222

Speelman L (1975) The seed distribution in band sowing of cereals. *Journal of Agricultural Engineering Research* 20:25-37

Stagnari F, Maggio A, Galieni A, Pisate M (2017) Multiple benefits of legumes for agriculture sustainability: an overview. *Chemical and Biological Technologies in Agriculture* 4, 10.1186/s40538-016-0085-1

Stanley KA, Shirtliffe SJ, Benaragama D, Syrovy LD, Duddu HSN (2018) Field pea and lentil tolerance to interrow cultivation. *Weed Technology* 32:205-210

[USDA, GIPSA] United States Department of Agriculture, Grain Inspection, Packers and Stockyards Administration (2006) Section 2.23 Plump Barley. Page 24 *in* Grain Inspection Handbook, Book II, Grain Grading Procedures. Washington, DC: USDA, GIPSA Federal Grain Inspection Service

[USFDA] United States Food and Drug Administration (2010) Guidance for Industry and FDA: Advisory Levels for Deoxynivalenon (DON) in Finished Wheat Products for Human Consuption and Grains and Grain By-Products used for Animal Feed. Silver Spring, MD: U.S. Food and Drug Administration

Warwick SI, Francis A (2005) The biology of Canadian weeds. 132. Raphanus raphanistrum L. *Canadian Journal of Plant Science* 85:709-733

Weiner J, Griepentrog H, Kristensen L (2001) Suppression of weeds by spring wheat Triticum aestivum increases with crop density and spatial uniformity. *Journal of Applied Ecology* 38:784-790

Welsh JP, Tillett ND, Home M, King JA (2002) A review of knowledge: inter-row hoeing and its associated agronomy in organic cereals and pulse crops. London, United Kingdom: Final report from Department for Environment, Food and Rural Affairs Funded Project *OF312.* 21 p

Zadoks JC, Chang TT, Konzak CF (1974) A decimal code for the growth stages of cereals. *Weed Research* 14:415-421

Zentner RP, Campbell CA (1998) First 18 years of a long-term crop rotation study in southwestern Saskatchewan: yields, grain protein and economic performance. *Canadian Journal of Plant Science* 68:1-21

BIOGRAPHY OF THE AUTHOR

Margaret McCollough was born in Bangor, Maine on June 18, 1992, and raised in Hampden, Maine by parents, Cathy Elliott and Mark McCollough. Margaret graduated from Hampden Academy in 2010 and attended the University of Maine, graduating in 2015 with a Bachelor of Science degree in Sustainable Agriculture. Before returning to the University of Maine to begin a Master's program, Margaret owned and operated a diversified organic vegetable farm in Arundel, Maine. After receiving her degree, Margaret will pursue a PhD in Agroecology at Aarhus University, where she will continue to study and research ecological weed management. Margaret is a candidate for the Master of Science degree in Ecology and Environmental Sciences from the University of Maine in August 2018.